APPLICATION

FOR

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TITLE: REAL-TIME EVALUATION OF STRESS FIELDS AND PROPERTIES IN LINE FEATURES FORMED ON SUBSTRATES

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REAL-TIME EVALUATION OF STRESS FIELDS AND PROPERTIES IN LINE FEATURES FORMED ON SUBSTRATES

This application claims the benefit of U.S. Patent

Application No. 09/560,719 filed July 29, 2002 which claims

5   from Provisional Application No. 60/200,499, filed on April

25, 2000.

BACKGROUND

This application relates to evaluation of stress fields

10   and properties in line features formed on substrates.

Measurements of various properties of a substrate and

features fabricated on the substrate may have important

applications. For example, manufacturing of certain devices

requires fabrication of various features and components on a

15   substrate (e.g., a semiconductor or a glass substrate). Such

substrate-based integrated devices include, among others,

integrated electronic circuits where micro circuit components

are formed on a semiconductor substrate, integrated optical

devices where micro optical components are fabricated on a

20   substrate, micro-electro-mechanical systems where micro

actuators and other mechanical components are fabricated on a

semiconductor substrate, flat panel display systems where

light-emitting elements, thin-film transistors and other

elements are fabricated on a transparent substrate (e.g., a

glass), or a combination of two or more of the above devices.

Different materials and different structures are usually

formed on the substrate and are in contact with one another.

5   Some devices may also use complex multilayer geometry. Hence,

the interfacing of different materials and different

structures may cause a complex stress state in each feature

due to differences in the material properties and the

structure properties at interconnections under different

10   fabrication processes and environmental factors (e.g.,

variations or fluctuations in temperature). In fabrication of

an integrated circuit, for example, the stress state of the

interconnect conducting lines may be affected by film

deposition, rapid thermal etching, chemical-mechanical

15   polishing, and passivation during the fabrication process.

It is desirable to measure stresses on various features

formed on the substrate to improve the design of the device

structure, selection of materials, fabrication process, and

other aspects of the devices so that the performance and

20   reliability of the device can be enhanced. The stress

measurements may be used to assess or evaluate the reliability

of materials against failure from such phenomena as

electromigration, stress-voiding and hillock formation. The

stress measurements may also be used to facilitate quality

control of the mechanical integrity and electromechanical functioning of circuit chip dies during large scale production in wafer fabrication facilities. In addition, the stress measurements may be used to improve the design of various

5 thermal treatments (such as temperature excursions during passivation) and chemical and mechanical treatments (such as polishing) to reduce their contribution to the residual stresses in the final device.

10 **SUMMARY**

A system according to one embodiment of the invention includes an optical detection module to obtain surface curvature information of a substrate-based device which has line features formed on a substrate, and a processing module

15 to produce stress information of the line features based on the curvature information. The optical detection module may include a coherent gradient sensing system to measure the surface gradient of a surface based on phase information in the wavefront of a reflected optical probe beam.

20 One method according to one embodiment includes first measuring a first curvature of a substrate at a location and along a longitudinal direction of a line feature formed at the location on the substrate and then measuring a second

curvature of the substrate at the same location along a transverse direction perpendicular to the longitudinal direction. Next, an analytical function is used to compute stresses on the line feature based on measured first and

5   second curvatures.

Alternatively, stresses of a line feature may be determined before the line feature is formed. In this method, curvatures of a substrate are measured before a film is deposited. Then the film is deposited on the substrate and

10   its curvature is measured. Next, the stress information of the deposited film is obtained and is used to determine stresses on a line feature to be patterned from the film based on an analytical function. This method can be extended to structures where line features are formed over two or more

15   underlying films on the substrate.

Another method determines stress information of line features embedded in trenches of a layer formed on a substrate. The curvatures of the embedded line features are measured by using an optical probe beam to obtain curvature

20   map of the illuminated area based on spatial gradient information in the reflected optical beam. Then measured curvatures are compared to curvatures of the line features computed from an analytical function. The deviation is then used to determine presence of residual stresses.

Yet another method measures curvatures of a line feature

and a film from which the line feature is formed as a function

of temperature to determine yield temperatures at which the

line and the film change their curvature dependence of the

5   temperature from a linear manner to a nonlinear manner. The

ratio between a yield stress of the line feature and a yield

stress of the film at their respective yield temperatures can

then be determined from an analytical function.

These and other features, and associated advantages of

10   will be apparent from the description and drawings, and from

the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a block diagram of a stress measurement system

15   according to one embodiment of the invention.

FIG. 2 illustrates one embodiment of a coherent gradient

sensing system.

FIG. 3 shows a coherent gradient sensing system having

two independent optical arms to obtain simultaneously spatial

20   shearing in two different directions.

FIG. 4A illustrates a top view of an exemplary structure

of a thermoelastic model according to one embodiment of the

invention.

FIG. 4B illustrates a cross-sectional view of the structure shown in FIG. 4A.

FIGS. 5 and 6 are flowcharts showing two methods of determining stresses of line features based on optical full-field surface curvature measurements.

FIG. 7 illustrates two exemplary subdivision areas of patterned line features on a substrate.

FIGS. 8A and 8B illustrate a model for line features embedded in a layer on a substrate and a model for line features embedded in a layer on a substrate and capped with a passivation layer.

FIG. 9 shows a flowchart for using the system shown in FIG. 1 to measure curvatures of line features embedded in a layer on the substrate.

DETAILED DESCRIPTION

The methods and systems of this application include at least an optical detection mechanism to measure curvature parameters of line features formed on a substrate and a

5 processing mechanism to extract stress information of the line features from the measured curvature parameters. The optical detection mechanism may provide a full-field measuring capability to simultaneously measure curvatures of one or more areas where line features are located, without the

10 conventional point-to-point scanning measurement. The processing mechanism may use only the curvature information to directly compute the stresses based on an analytical formulation to eliminate complex numerical computation. Hence, the stress information can be obtained within a short

15 processing time. This combination of the full-field optical detection and the processing can produce a spatial map of the stress distribution in the area under measurement in virtually real time so long as the change in the stress is slower than the processing time.

20 FIG. 1 shows a stress measurement system 100 according to one embodiment which includes an optical detection module 102 to implement the optical detection mechanism and a data processing module 105 to implement the processing mechanism. The optical detection module 102 produces an illumination

optical beam 103 to a surface of the sample substrate 130 and then detects the reflected beam 104. The illumination beam 103 is directed so as to illuminate an area which includes one or more areas having line features under measurement. The

5   reflected beam 104 from the sample substrate 130 is then optically processed to produce an optical pattern that has the curvature information of the entire illuminated area. This optical pattern is converted into a curvature signal 106. The signal is sent to the processing module 105 which may include

10   an electronic processor or other type of processor. The curvature signal 106 may be an electronic signal representing the optical pattern. The signal is then processed to produce curvature data for the entire illuminated area on the substrate 130. The processing module 105 produces desired

15   stress data on line features formed on any one or more desired locations in the illuminated area on the substrate 130 based on respective curvature data.

FIG. 2 shows one embodiment of a coherent gradient sensing ("CGS") system 200 as an implementation of the optical

20   detection module 102. See, U.S. Patent No. 6,031,611 to Rosakis et al. The CGS system 200 uses a collimated coherent optical beam 112 from a light source 110 as an optical probe to obtain curvature information indicative of a specularly reflective surface 130 formed of essentially any material. An

optical element 120 such as a beam splitter can be used to direct the beam 112 to the surface 130. When the reflective surface 130 is curved, the wavefront of the reflected probe beam 132 is distorted and thereby the reflected probe beam 132

5   acquires an optical path difference or phase change associated with the curvature of the surface 130 under measurement. This system produces a "snapshot" of each point within the illuminated area on the surface 130 and hence the curvature information at any point along any direction within the

10 illuminated area can be obtained. This can eliminate the need for measuring one point at a time in a sequential manner by using a scanning system.

Two gratings 140 and 150 spaced from each other are placed in the path of the reflected probe beam 132 to

15 manipulate the distorted wavefront for curvature measurement. Two diffraction components produced by the second grating 150 diffracting two different diffraction components produced by the first grating 140 are combined, by using an optical element 160 such as a lens, to interfere with each other. The

20 diffraction by the two gratings 140 and 150 effectuates a relative spatial displacement, i.e., a phase shift, between the two selected diffraction components. This phase shift is a function of the spacing between the two gratings 140 and 150 when other grating parameters are fixed. A spatial filter 170

is placed relative to the optical element 160 to transmit the interference pattern of the selected diffraction components and to block other diffraction orders from the second grating 150.

5   The transmitted interference pattern is then captured by an imaging sensor 180 which may include an array of sensing pixels, such as a CCD array, to produce an electrical signal representing the interference pattern. A signal processor 190, which may be part of the processing module 105 in FIG. 1,

10   processes the electrical signal to extract a spatial gradient of the phase distortion caused by the curvature of the reflective surface 130. This spatial gradient, in turn, can be further processed to obtain the curvature information and hence a curvature map of the illuminated area on the surface

15   130 can be obtained. A single spatial differentiation is performed on the interference pattern to measure the surface gradient. This technique can provide accurate measurements of surface curvatures when the curvature variation of the surface is gradual, i.e., when the out-of-plane displacement is less

20   than the thickness of the film, the line or the substrate. This technique is insensitive to rigid body motion in comparison with some other interferometric techniques. Details of this data processing operation are described in the above-referenced U.S. Patent No. 6,031,611 to Rosakis et al.

The two gratings 140 and 150 in general may be any

gratings, with different grating periods and oriented with

respect to each other at any angle. Preferably, the two

gratings may be oriented with respect to each other in the

5   same direction and may have the same grating periods to

simplify the data processing. In this case, the grating

direction is essentially set by the direction of the relative

spatial displacement ("shearing") between the two selected

diffraction components due to the double diffractions by the

10   gratings 140 and 150.

Certain applications may require spatial shearing in two

different directions to obtain a full-field two-dimensional

curvature measurement. This may be done by using the CGS

system 200 to perform a first measurement when the sample

15   surface 130 is at a first orientation and subsequently to

perform a second measurement when the sample surface 130 is

rotated to a second orientation (e.g., perpendicular to the

first orientation). Alternatively, a two-arm CGS system,

shown in FIG. 3 may be implemented to have two separate sets

20   of double gratings in two different directions to

simultaneously produce the interference pattern in two

different spatial shearing directions. Hence, time-varying

effects in the curvature distribution in both spatial shearing

directions can be obtained.

The above CGS systems may be used to measure curvatures of various features and components formed on a substrate either directly or indirectly. In the direct measurement, the probe beam in the CGS can be directly sent to the top surface of these devices to obtain the curvature information. This usually requires that the surface features and components and their surrounding areas are preferably smooth and optically reflective. In addition, it is desirable that properties of the features and components and their surrounding areas other than their curvatures do not significantly contribute to the wavefront distortion. Hence, the wavefront distortion can be used as an indicator of the curvatures of the area illuminated by optical probe beam. For example, some completed integrated circuits have a top passivation layer, usually made of a non-conductive dielectric material, over the circuit elements on the substrate to protect the underlying circuits. The surface of the passivation layer is in general smooth and is sufficiently reflective for CGS measurements.

However, the above conditions may not be met in some other substrate-based devices. For example, features and components formed on the front side of a substrate or their surrounding areas may not be optically reflective. The features and components on the front side may distort the reflected wavefront due to factors other than the curvatures,

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such as the height of a feature or component being different

from its surrounding areas. In these cases, the curvatures of

the features or components may be indirectly measured by

inference from the curvature measurements of the corresponding

5   locations on the opposite surface on the back side of the

substrate. This is possible because the stresses in the non-

continuous features and components formed on the substrate can

cause the substrate to deform and the thin films formed over

the substrate generally conform to the substrate surface.

10   When the heights of certain features are different from

their surroundings, the phase distortion on the wavefront of

the reflected probe beam for each feature includes at least

the portion contributed from the height difference and the

portion contributed from the curvatures. In addition to using

15   the back side of the substrate for the CGS measurement, the

CGS measurement may also be performed by illuminating the

front side. The curvature information can thus be extracted

by removing the effects of the height difference in

computation of the curvatures if the height information is

20   known.

In addition to curvature measurements of a completed

substrate-based device, the CGS technique can also be used to

perform in-situ curvature measurements of a substrate and each

layer or feature during each fabrication step of a substrate-

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based device. The CGS technique can achieve this due to its full-field capability of simultaneously measuring the curvatures of all locations within an illuminated area. Therefore, each measurement can be performed and completed in

5 a short time without interrupting the fabrication sequence. Because the CGS technique uses an optical probe beam as the probe to obtain the curvature information, the measurement is non-invasive and hence does not interfere with the fabrication process when the intensity of the optical probe beam is

10 properly kept below an acceptable level. In addition, the optical probe beam and its reflected beam from the substrate can be conveniently guided to and from the substrate in a processing chamber through one or more optical windows in the processing chamber.

15   Therefore, during the fabrication of the thin-film layers and various features in each layer, the curvatures and associated stresses of each layer and each feature formed in each layer may be monitored with the CGS technique. This in-situ stress monitoring mechanism may be applied to various

20 aspects of the substrate fabrication.

        For example, this in-situ stress monitoring mechanism may be used to screen out a defective batch of processed substrates at any intermediate stage during the fabrication prior to completion of the entire fabrication processes. It

is known that fabrication process and associated thermal

cycling can introduce stresses in fabricated features. For

example, the various metallization processes are carried out

at elevated temperatures. Also, the layers may exhibit

5   different mechanical, physical and thermal properties which

can lead to high stresses in interconnection structures due

to, e.g., mismatch in the amounts of thermal expansion and

contraction between dissimilar materials. These stresses can

cause, among others, undesired stress-induced voiding and

10   interfacial cracking, and can contribute to electromigration.

In addition, the stresses may cause cracking of the substrate.

Voiding, electromigration, and substrate cracking are among

the leading failure factors in integrated circuits.

Some of the defects are caused by stresses after an

15   intermediate step during the fabrication. A device is

defective when the stresses at various parts exceed

predetermined acceptable values. The above in-situ stress

monitoring can be used to measure the stresses at selected

stages or continuously during the fabrication. The measured

20   stresses are compared to the acceptable values. If a measured

stress is greater than its acceptable value, a defect is

discovered. The fabrication process may be terminated since

the final device would be defective. Thus, the remaining

fabrication steps need not be carried out. This avoids the

wasteful and inefficient practice in some conventional

fabrication methods where the defects of the fabricated

devices are tested only after the entire fabrication processes

are completed.

5   Another exemplary application of this in-situ stress

monitoring mechanism is adjustment and optimization of the

processing parameters and conditions in fabrication to reduce

the stresses in the substrates.   Because the CGS technique can

be used to monitor the stresses in situ during the

10   fabrication, contributions to the stresses from different

processing steps can be identified by monitoring the stresses

at each processing step.   In addition, the processing

parameters (e.g., temperature, duration or duty cycle) of each

processing step may be adjusted either independently or in

15   reference with the processing parameters of other processing

steps to reduce the stresses.   Effects on the stresses may be

measured by the CGS technique upon each adjustment so that a

relation between the parameter and the stresses can be

established.   The steps of adjusting a processing parameter

20   and measuring the resultant stresses may be carried out in an

iteration process until the resultant stresses are reduced to

satisfactory levels.   Hence, the processing steps can be

controlled to increase the overall yield of the fabrication.

Yet another application of the CGS technique is to monitor large surface deformation which has an out-of-plane displacement greater than the thickness of the line and the substrate. Although the accuracy of the CGS measurements

5 deteriorates if the surface deformation is no longer small compared to thickness of the line and the substrate, this deviation of the CGS measurements from predicted curvature values may be used as an indicator of presence of uniform, large surface deformations if the CGS system is used for in-

10 situ monitoring.

Referring back to FIG. 1, after the curvature map is obtained, the processing module 106 then processes the curvature map to produce a corresponding stress map of the illuminated area on the sample surface. This is an important

15 aspect of the system 100 shown in FIG. 1 and is accomplished by using a simple analytical formulation to compute the stresses on a feature from the curvature data and the material parameters of the substrate and the feature material.

In one implementation, the processing is based on a

20 thermoelastic model for thin periodic line features formed on a thick substrate as described below. Certain aspects of the thermoelastic model, including detailed calculation steps, are disclosed by Wikstrom, Gudmundson, and Suresh, in "Thermoelastic Analysis of Periodic Thin Lines Deposited on A

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Substrate," Journal of the Mechanics and Physics of Solids,

vol. 47, pp. 1113-1130 (May, 1999).

FIGS. 4A and 4B schematically illustrate the structure of

the thermoelastic model according to one embodiment. Multiple

5   identical line features 402 are formed on a surface of a

substrate 400. The line features 402 each have a width b and

a thickness or height t and are evenly spaced from one another

by a spacing d to form a periodic pattern. It is assumed that

the dimension of the substrate 400 (e.g., diameter) is much

10   greater than the thickness, h, of the substrate 400. For

example, it may be sufficient for practical purposes that is

at least 10 times, or preferably 50 times, greater than h in

some devices. It is also assumed that both the thickness, t,

and the width, b, of each line feature 402 are much less than

15   the longitudinal length l and the thickness h of the substrate

400, by at least a factor of 10, for example, 25 or greater.

The accuracy of the model depends on these assumptions: the

accuracy generally increases as these factors increase.

Under these assumptions, the substrate 400 may be treated as a

20   homogenized anisotropic plate.

A Cartesian coordinate system (x_1, x_2, x_3) is established in

FIGS. 4A and 4B for the thermoelastic model. The directions

marked x_1 and x_2 represent the directions along and across the

line features, respectively, in the plane of the substrate

400. The direction marked x_3 represents the direction normal

to the plane of the substrate 400. The volume average value

of any quantity A over some volume V is defined as

5
$$\overline{A} = \frac{1}{V} \int_v A(x_1, x_2, x_3) \, dV.$$

Based on the analysis by Wikstrom et al., supra., the volume-

averaged stresses in each line feature 402 can be expressed in

terms of the curvature k_1 along the x_1 direction (i.e.,

10 longitudinal), the curvature k_2 along the x_2 direction (i.e.,

transverse) of the substrate 400:

$$\begin{bmatrix} \overline{\sigma_{11}} \\ \overline{\sigma_{22}} \\ \overline{\sigma_{12}} \end{bmatrix} = \frac{-E_s}{6(1-\upsilon_s^2)} \frac{h^2}{t} \frac{d}{b} \begin{bmatrix} 1 & v_s & o \\ v_s & 1 & o \\ o & o & \frac{1-v_s}{2} \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ o \end{bmatrix}, \qquad (1)$$

15 where $\sigma_{\alpha\beta}$ represents the stress tensor components (α, β=1, 2),

and E_s are v_s are Young's modulus and Poisson's ratio of the

substrate 400, respectively. The volume average of the shear

stress σ_{12} is zero in this case. The negative sign "-" in

Equation (1) is used to implement an elected sign convention,

20 i.e., a positive value represents one direction of the

curvature while the negative value represents the opposite

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direction of curvature. Notably, each stress component is a linear sum given by $f_1(E_s, v_s, h, t, d, b).k_1 + f_2(E_s, v_s, h, t, d, b).k_2$, where coefficients f_1 and f_2 are functions of E_s, v_s, h, t , d, and b. Therefore, the stresses of each line feature can be

5   computed based on elastic properties of the substrate and the geometry of the line features.

Hence, measurements of curvatures of the substrate 400 at each line feature 402 allow determination of volume-averaged elastic stresses by a simple analytical function based on

10   dimension parameters of the substrate 400 and each line feature 402, the elastic properties of the substrate 400 (e.g., Young's modulus and Poisson's ratio). One of the features of this method is that the stress computation of Equation (1) does not require any detailed information on the

15   material composition, the mechanical and other properties of the line feature itself. Although these characteristics of the line feature are among the primary factors that determine the stress behaviors of the line feature, the effects of these characteristics are included in the measured curvatures along

20   and cross the line feature, k_1 and k_2.

Another feature of this method is that Equation (1) is a simple analytical formula and hence the stress computation based on the measured curvatures k_1 and k_2 can be carried out by a processor in a short time. For example, a microprocessor

can be used to implement a computer routine to carry out the

computation shown in Equation (1). Hence, complex and time-

consuming numerical computations are essentially avoided. In

addition, the simple analytical formula in Equation (1) has

5   been shown to be accurate in comparison with complex numerical

computations based on finite element analysis (Wikstrom et

al., supra.). This feature of the data processing module,

when combined with the full-field parallel processing of the

CGS optical detection module, allows the stress measurement

10   system 100 of FIG. 1 to measure the curvatures of a location

and generate the respective stresses at a relatively high

speed. Therefore, the system 100 may be used to measure

temporal changes of curvatures and associated stresses of a

line feature in real time for many processes of semiconductor

15   fabrication.

The above stress computation method with respect to

Equation (1) provides a way of obtaining stress data of a line

feature on a substrate if the information on a thin film from

which the line feature is formed is not available. An example

20   of this situation is to determine the stresses in a device

after the line feature is formed from a thin film such as a

completed IC circuit.

FIG. 5 shows a flowchart of the above stress measurement

method based on Equation (1). Such stress measurement can be

performed either after the fabrication of the substrate is

completed or during the fabrication as an in-situ monitoring

mechanism.

An alternative method of the present application can be

5   used to determine the stresses of line features patterned from

a thin film on a substrate even before the line features are

formed if the curvatures of the substrate and the thin film

can be measured prior to patterning. One example of this

situation is in-situ measurements during the fabrication by

10   using the curvature measurement system 100 shown in FIG. 1.

First, before any layer is formed over the substrate, the

curvature map of the bare substrate is measured (so is the

associated stress map). When the substrate and the subsequent

deposited continuous film thereon are essentially isotropic,

15   the curvature at any location should be identical along any

direction. Next, after a thin film is deposited on the

substrate, the curvature map of the continuous film is

measured. The stress in the unpatterned and continuous film

at a location of interest can be determined from Stoney's

20   equation:

$$\sigma_{film} = \frac{-E_s}{6(1-v_s)} \frac{h^2}{t} \left[k_{film} - k_s \right] \qquad (2)$$

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where k_{film} and k_s are the measured curvatures of the deposited film and the bare substrate at the same location of interest, respectively. Here, the sign convention is elected so that the curvature is positive when the substrate surface on which

5   the film is deposited is convex and negative when the surface is concave.

If periodic line features are formed on this film, the curvatures across and along each line feature, k_1 and k_2, respectively, can be determined from elastic properties of the

10 film and the substrate, and the geometry of the line featueres by the following analytical formula:

$$\begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = k_{film}\frac{d}{b}\begin{bmatrix} 1 \\ 1 \end{bmatrix} - \frac{\chi}{1-v_s}\begin{bmatrix} v_{film} - v_s \\ 1 - v_s v_{film} \end{bmatrix}, \qquad (3)$$

15 where v_{film} is the Poisson's ratio of the film, χ is given by

$$\chi \approx (3.95138)\frac{t}{b}\sum_{j=1}^{10}\frac{d_j}{\left(1+\frac{t}{b}\right)^j},$$

and coefficient d_j is given in TABLE 1. Note that when

20 $\frac{t}{b} \to o, \chi \to 0$ and $\frac{t}{b} \to \infty, \chi \to 1$. See, Wikstrom et al., supra.

Here, it is assumed that the changes in curvatures from k_{film} to k_1 and k_2 are caused solely from changes in geometry from

patterning the film into line features. It also assumed that the elastic properties of the line features are essentially the same as the film.

5

TABLE 1

Coefficients d_j	
j	**d_j**
1	0.25256
2	0.27079
3	−0.49814
4	8.62962
5	−51.24655
6	180.96305
7	−374.29813
8	449.59474
9	−286.51016
10	73.84223

Accordingly, the volume-averaged elastic stresses on each line feature can be obtained from the following equation:

10

$$\begin{bmatrix} \overline{\sigma_{11}} \\ \overline{\sigma_{22}} \\ \overline{\sigma_{12}} \end{bmatrix} = \sigma_{film} \begin{bmatrix} 1 - \chi \upsilon_{film} \\ 1 - \chi \\ 0 \end{bmatrix}. \qquad (4)$$

This method, like the previous method, uses a simple analytical formulation of Equations (2), (3), and (4) to compute the stresses on each line feature. Unlike the

15 previous method, however, the curvature of the substrate required in Equation (2) is measured before the film is deposited while the curvatures k_1 and k_2 of the substrate

required in Equation (1) are measured after the line features

are formed on the substrate. Hence, this method can be used

to predict the stresses of line features to be formed. FIG. 6

shows a flowchart of the stress measurement based on Equation

5   (4).

In addition, the analytical formulation of Equations (2),

(3), and (4) can also be applied to lines formed over one or

more thin films on the substrate. In this case, the parameter

k_s in Equation (2) is the total curvature of a structure

10   formed by the underlying films and the substrate before the

line-forming film is deposited. This total curvature can be

directly measured by using the CGS method. To a first order

approximation, the total curvature is the sum of curvatures

that would be induced if each individual layer would be

15   deposited by itself on the substrate.

The above stress measurement techniques can be applied to

measure a substrate with line features that are oriented in

more than one direction, for example, in mutually orthogonal

directions. The entire area of interest on the substrate may

20   be divided into two or more subdivision areas depending on the

pattern formed thereon so that each subdivision area only has

line features that are parallel to one another along one

direction. Thus, the model for unidirectional line features

as shown in FIGS. 4A and 4B is applicable to each individual

subdivision area to compute the corresponding stresses based
on the curvature data from the CGS measurement. A non-
straight single conductive line hence may include two or more
different segments in different subdivision areas. The
5   stresses in this line are obtained by computing stresses in
different segments based on the CGS curvature data.

FIG. 9 shows a portion of line features formed on a
substrate which includes two subdivision areas A and B. The
directions of line features in each subdivision area are the
10 same. The subdivision areas A and B may be selected in such a
way that the distance from the edge in each area to the
nearest sharp corner where the lines change direction is at
least the greater value of one line width b or thickness t of
each line feature. This condition can maintain the accuracy
15 of the stress computation based on the model in FIGS. 4A and
4B. The subdivision areas A and B may be measured
simultaneously in time by using the system 100 of FIG. 1 when
the optical probe beam is directed to illustrate both areas A
and B at the same time.

20 In many practical devices, line features formed over a
substrate are often embedded in a different material. For
example, conductive lines are often embedded in an insulating
conductive material such as an oxide. The model shown in
FIGS. 4A and 4B is no longer applicable to the analysis of

curvatures and stresses of such structures. In fact, it is difficult to compute stresses in such embedded line features without complex numerical computation. However, a new model can be used to compute curvatures of an embedded line feature

5   based on the structure design, material properties of the embedded line features and the surrounding material.

FIG. 8A illustrates a model for computing curvatures of line features 810 embedded in trenches of a layer 820 formed on a substrate 800. Similar to the model in FIGS. 4A and 4B,

10   the transverse dimension of the substrate 800 is assumed to be much greater than its thickness h. The line features 810 are parallel and are evenly spaced by a spacing d on the substrate 800 along the x_2 direction. The width b and the thickness t of each line feature 810 are also assumed to be much less than

15   its longitudinal length along the x_1 direction and the thickness h of the substrate 800. See, Park and Suresh, "Effects of Line and Passivation Geometry on Curvature Evolution during Processing and Thermal Cycling in Copper Interconnect Lines," Acta Materialia (April, 2000).

20   It is further assumed that, the aspect ratio, $f_o = t/b$, of the line features 810 and the aspect ratio of the lines formed in surrounding layer 820, $f_1 = t/(d-b)$, are comparable to or larger than unity, and that, the curvatures along and across the line features 810 do not influence one another for elastic

deformation. According to Park and Suresh, supra., the curvature k_1 of the line features 810 along the line direction x_1 and the curvature k_2 perpendicular to the line direction x_1 caused by a change in temperature ΔT within the elastic range

5   can be expressed as

$$k_1 = \frac{6}{E_s} \frac{t}{h^2} E_1 (\alpha_1 - \alpha_s)\Delta T, \qquad (5)$$

$$k_2 = \frac{6}{E_s} \frac{t}{h^2} E_2 (\alpha_2 - \alpha_s)\Delta T, \qquad (6)$$

10 where

$$E_1 = f_l E_l + f_o E_o = \frac{b}{d}E_l + (1 - \frac{b}{d}), \qquad (7)$$

$$E_2 = \frac{E_l E_o}{f_l E_0 + f_0 E_l}, \qquad (8)$$

$$\alpha_1 = \frac{f_l E_l \alpha_l + f_0 E_0 \alpha_0}{f_l E_l + f_o E_o}, \qquad (9)$$

15

$$\alpha_2 = f_l \alpha_l + f_o \alpha_o + \frac{f_l f_o (v_l E_o - v_o E_l)(\alpha_l - \alpha_0)}{f_l E_l + f_o E_o} \qquad (10)$$

and E_1, v_1, and α_1 are Young's moduli, Poisson's ratio, and

20 coefficient of thermal expansion for the line features 810,

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respectively, and E_o, v_o, α_o are Young's moduli, Poisson's ratio, and coefficient of thermal expansion for the layer 820, respectively. In the composite analogy, the layer comprising

5 the line features 810 (e.g., Cu lines) and the surrounding layer 820 (an oxide such as silicon dioxide) is homogenized as an anisotropic composite layer with Young's moduli E_1 and E_2 along and across the line direction, respectively, and with thermal expansion coefficients, α_1 and α_2, along and across the line direction, respectively.

10 The predictions of this simple analytical analysis have been shown to be reasonably close to the results of more detailed finite element simulations, with a deviation from about 3% to about 17%. For some practical configurations of Cu lines in oxide trenches, the error is typically smaller

15 than 17%.

FIG. 8B shows another model where a capping passivation layer 830 is formed over the line features 810 and the layer 820. Assuming the passivation layer 830 is much thinner than the substrate 800, the curvatures of the passivated line

20 features 810, due to elastic deformation caused by a change ΔT in temperature, can be expressed as

$$k_1^{pass} = \frac{6}{E_s}\frac{t}{h^2}E_1\left(\alpha_1-\alpha_s\right)\Delta T + 6\frac{h_p}{h^2}\cdot\frac{E_p}{E_s}\cdot\frac{\left(1-v_s\right)}{\left(1-v_p\right)}\left(\alpha_p-\alpha_s\right)\Delta T, \qquad (11)$$

$$k_2^{pass} = \frac{6}{E_s} \frac{t}{h^2} E_2 \left(\alpha_2 - \alpha_s\right)\Delta T + 6\frac{h_p}{h^2} \cdot \frac{E_p}{E_s} \cdot \frac{\left(1-\nu_s\right)}{\left(1-\nu_p\right)}\left(\alpha_p - \alpha_s\right)\Delta T, \qquad (12)$$

where E_p, ν_p, α_p are Young's modulus, Poisson's ratio, and

5   coefficient of thermal expansion for the passivation layer

830, respectively.

The above models shown in FIGS. 8A and 8B can be used to

compute the curvatures of embedded lines on the substrate

based on the certain known parameters of the substrate-based

10   devices. Although the stresses of the embedded lines cannot

be directly computed from Equations (5)-(12), the models can

be implemented in the processing module 105 of the system 100

shown in FIG. 1 to determine whether residual stresses exist

in the devices.

15   FIG. 9 shows a flowchart of combining the CGS

measurements with the curvature estimation based on the models

in FIGS. 8A and 8B to determine the stress information of the

embedded lines. First, the curvatures of embedded lines of a

device are measured by the CGS method and computed based on

20   the models in FIGS. 8A and 8B. The CGS measurements provide

actual curvatures of the lines while the computed curvatures

are only the curvatures caused by elastic deformation. Next,

the computed curvatures and the measured curvatures are

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compared. Their differences indicate the curvatures caused by residual stresses which are not included in the computation. The residual stress should be kept below an acceptable level in order to ensure the normal operation and a desired lifetime

5   of the device. Hence, when the difference either along or cross the line exceeds the acceptable level, the liability or performance of device may be considered as being unacceptable.

The above process can be used to monitor the stresses in the embedded lines during the fabrication process because the

10   CGS is capable of in-situ measurements. The differences in curvatures between the analysis and CGS measurements provide an indication what actually is going on with respect to stress/curvature evolution that is not accounted for in design. Hence, one or more aspects of the fabrication or the

15   design of the devices may be examined and modified to reduce the residual stresses within the acceptable range. In addition, the in-situ measurements may also be used to terminate the fabrication prior to the completion of the entire process if the residual stresses exceed above the

20   acceptable level at an intermediate step. This monitoring mechanism may reduce the cost and increases fabrication efficiency.

Equations (5), (6) and (11), (12) may also be used to fit measured curvature data to determine a property of the line

features or the substrate, such as the Young's modulus, the

coefficient of the thermal expansion, and Poisson ratio of the

substrate or the line feature. For example, in devices with

the passivation layer 830, the CGS measurements of the

5   curvatures may be used to determine properties of the

passivation layer 830 based on Equations (11) and (12). The

biaxial modulus of the passivation layer 830, $E_{p,B} = E_p/(1- \upsilon_p)$

can be computed from the CGS measurements of k_1^{pass} and k_2^{pass}

that are made during the process before and after the

10   passivation layer is deposited.

The above method for measuring embedded lines can be

applied to a new fabrication technique for making copper

conductive lines in oxide trenches, "Damascene process." With

this technique, trenches are etched in an oxide layer to

15   conform to the geometry of the copper interconnect lines in

the circuit formed on a Si substrate. The etching is

performed by using a dry etching process. These oxide

trenches are then plugged with Cu with the use of chemical

vapor deposition (CVD) or electroplating. The extra copper

20   above the trenches is then removed by chemical-mechanical

polishing (CMP), and then a passivation or a capping layer is

deposited on top of the interconnect structure.

Since the Damascene process involves material removal by

polishing, the knowledge of curvature evolution during

polishing and subsequent processing is essential on various

counts. For example, in-situ monitoring of curvatures using

the CGS method can provide information on the "flatness" of

the polished surface upon which layers are deposited. This

5 can be an essential step in quality control. Also, a

knowledge of curvature evolution can also give an indication

of the evolution of internal stresses during fabrication.

Furthermore, the above analysis for unpassivated and

passivated lines can also be used to simulate the evolution of

10 elastic stresses during thermal cycling, and can be readily

compared with CGS measurements. Examples of such calculations

are given in Park and Suresh, and are verified by comparisons

with finite element simulations.

In addition to measuring the stresses caused by elastic

15 changes, the system 100 shown in FIG. 1 may also be

configured, based on the model in FIGS. 4A and 4B, to

determine some plastic properties of line features formed on a

substrate. Line features formed on a substrate may be subject

to permanent and plastic deformation under certain

20 thermomechanical treatments. In general, a line feature and

the thin film experience elastic deformation when the

temperatures are below threshold yield temperatures T_l^Y and

T_f^Y, respectively. The curvatures of elastic deformation

change linearly with the temperatures. When the temperatures

are above the threshold yield temperatures T_1^Y and T_f^Y,
however, plastic deformation occurs and the curvatures change
with the temperatures in a nonlinear manner. For example,
plastic deformation may occur in conductive lines when heated
5   above the yield temperature during passivation. It is
desirable to determine the stresses caused by such plastic
deformation.

Suppose that the initial stress-free temperature of a
line feature and the continuous film from which the line
10   feature is patterned on the substrate are T_1^0 and T_f^0,
respectively. The stress-free temperature ranges of the
line/substrate and film/substrate systems can be determined
experimentally using the CGS technique to measure the
curvatures as a function of temperature. The curvature of the
15   unprocessed continuous film may be determined based on
Equation (2) as described above. The temperature change, from
the initial stress-free temperature, to initiate plastic
yielding in the line and the film, respectively, can be
written as:

20

$$\Delta T_\ell^Y = T_\ell^1 - T_\ell^0 = \frac{1-\upsilon_f}{E_f\left(\alpha_s-\alpha_f\right)} \frac{\sigma_\ell^Y}{Z^e}, \qquad\qquad (13)$$

$$\Delta T_f^Y = T_f^1 - T_f^0 = \frac{1-\upsilon_f}{E_f\left(\alpha_s - \alpha_f\right)}\ \sigma_f^Y. \tag{14}$$

where Z^e is given by

$$Z^e = \left\{\left(1-\chi\upsilon_f\right)^2 - \left[\chi\left(1-\chi\right)\left(1-\upsilon_f\right)\right]\right\}^{1/2}. \tag{15}$$

5

where T_1^Y and T_f^Y are temperatures at which permanent, plastic

deformation begins to occur in the line feature and the

continuous film. At temperatures above T_1^Y and T_f^Y, the

curvatures of the line and the film begin to change

10 nonlinearly with temperature. Equations (13)-(15) can be

derived based on the model in FIGS. 4A and 4B based on an

analysis by Gouldstone, Wikstrom, Gudmundson and Suresh in

"Onset of Plastic Yielding in Thin Metal Lines Deposited on

Substrates", Scripta Materialia, vol. 41, No. 3, pp. 297-304,

15 (August 1999).

From Equations (13) and (14), the following can be

obtained

$$\frac{\Delta T_\ell^Y}{\Delta T_f^Y} = \frac{\sigma_\ell^Y}{\sigma_f^Y}\frac{1}{Z^e}. \tag{16}$$

20

Because the ratio of the temperature difference can be

measured by using the CGS technique and the parameter Z^e can

be calculated based on Equation (4), the ratio of the yield stresses of the line feature and the film can be determined from Equation (16). Thus the CGS method, in conjunction with the above analysis, provides a useful tool for determining the

5   onset of yielding in patterned lines.

The above methods and systems may be used to measure, in real time, the history and spatial variation of stresses on the substrate, line features or films formed thereon. In particular, measurements from the coherent gradient sensing

10   method can be rapidly processed by analytical computations to obtain spatial and temporal variations of stresses and plastic strains. Information on plastic deformation of the line features and films on the substrate can also be measured.

A number of embodiments of the invention have been

15   described. Nevertheless, it will be understood that various modifications and enhancements may be made without departing from the following claims.